World Journal of Environmental Biosciences
Available Online at: **www.environmentaljournals.org**

Volume 14, Issue 1: 29-36

https://doi.org/10.51847/WQw5nbKWTx

ISSN 2277- 8047

Indoor Air Pollution in Urban Environments: A Case Study of Air Quality in Pune, Maharashtra

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ABSTRACT

Indoor air pollution refers to the air quality within enclosed spaces like homes, schools, offices, and vehicles. In cities like Pune, it has worsened due to sealed buildings, limited ventilation, and the use of synthetic materials. This study assessed indoor air quality (IAQ) across various locations in Pune, revealing that many areas exceed safe pollution levels. High concentrations of volatile organic compounds (VOCs) were detected in public transport and vehicles, while hotels showed the highest particulate matter (PM) levels. Poor ventilation further aggravated indoor pollution. In contrast, commercial spaces had relatively better IAQ due to improved airflow and design. Public transport showed the highest air quality index (AQI) values, posing health risks to commuters. Overall, poor IAQ is a growing health concern. The study highlights the urgent need for better ventilation, effective air purification systems, and public awareness to reduce exposure to indoor pollutants and promote healthier living environments.

Keywords: *Indoor air quality, Pollution, Ventilation, VOCs, Particulate matter*

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Received: 07 January 2025
Accepted: 18 March 2025

INTRODUCTION

Air pollution poses a significant environmental challenge in India, exacerbated by rapid urban expansion and population density (Vohra *et al.,* 2022). Common sources include combustion, building materials, and bioaerosols, with pollutants like radon, VOCs, and particulate matter (PM) posing significant health risks (Kumar *et al.,* 2023). Pollutant levels in Indian cities like Bengaluru often exceed WHO standards for PM10, PM2.5, SO_2, NO_2, and CO_2, increasing respiratory disease risks and highlighting the need for decentralized air quality monitoring (Wu *et al.,* 2024).
Indoor air quality is vital for health and well-being and establishing scientifically sound limits for indoor pollutants is imperative (Zhang *et al.,* 2021). Research indicates that outdoor pollutants significantly affect indoor air quality, with seasonal variations influencing pollutant levels (Chen *et al.,* 2024). Advancements in smart technologies, such as AI-driven prediction systems, present new solutions for IAQ monitoring, facilitating timely interventions (Mahule *et al.,* 2024). As urbanization advances, integrating strategies that address both indoor and outdoor air quality will be crucial for public health and environmental sustainability (Ouma *et al.,* 2024). In India, the National Ambient Air Quality Standards (NAAQS) set by CPCB (2009) specify safe limits for key pollutants: PM10 (100 $\mu g/m^3$), PM2.5 (60 $\mu g/m^3$), SO_2 and NO_2 (80 $\mu g/m^3$) over 24 hours, and CO (2.0 mg/m^3 over 8 hours). These standards are designed to protect public health.
A large part of India's population faces unhealthy air, making pollution a major cause of disease and mortality, especially in densely populated areas (Balakrishnan *et al.*, 2019). The Airborne Infrared Observing System (AIRO), a decentralized IoT-based air quality monitor, calculates real-time AQI, aiding in tracking and regulating pollutants (Kumar & Doss, 2022). Dimitroulopoulou *et al.* (2023) investigated pollutant limits and environmental factors that impact health, efficiency, and moisture-related issues. Future advancements in sensors, IAQ-monitoring systems, and smart home technologies present promising solutions for improving indoor air quality (Van Tran *et al.*, 2020). Settimo *et al.* (2020) found that PM levels in a naturally ventilated Delhi school exceeded limits, with an I/O ratio above one, driven by ventilation, traffic, and occupant activities. In South Korea, the Indoor Air Quality Control Act was enacted in 1996, followed by Taiwan in 2012. Lim *et al.* (2024) analyzed IAQ in public facilities before and after Taiwan's IAQM Act to assess its impact. Health risks for employees and visitors showed increased CO_2 and formaldehyde levels post-IAQM Act, except in some facilities, while PM2.5 levels improved in hospitals and libraries (Ouma *et al.,* 2024). There is need for expanded measurement data post-IAQM Act and the development of risk-based management strategies for future research (Pignon *et al.*, 2022; Pande *et al.*, 2024). Dhaka, Bangladesh's capital, is an air pollution hotspot among megacities, but meteorological influences on its criteria air pollutants remain underexplored (Jaganathan *et al.*, 2025). Such research aims to examine the relationships between

meteorological parameters and the concentration of criteria air pollutants (Rahman *et al*., 2024).

Pune, situated at 560 meters above sea level on the western edge of the Deccan Plateau, has varied topography with elevations up to 800 meters and a diverse climate shaped by the Western Ghats. Covering 484.61 square kilometers, its historical and ecological significance makes it ideal for indoor air quality research. Pune's AQI (2021-2024) peaked at 125.88 (2023) before dropping to 96.69 (2024), remaining above India's safe limit (AQI ≤60). (Source: CCR, CPCB). This study evaluates IAQ through subjective surveys and objective measurements of PM2.5, PM10, formaldehyde, temperature, and humidity.

MATERIALS AND METHODS

Ten polluted or densely populated locations were assessed using the TEMTOP LKC-1000S monitor and a questionnaire on occupants' perceptions. The 7-in-1 TEMTOP LKC-1000S measures PM2.5, PM10, formaldehyde (HCHO), AQI, temperature, and humidity, providing accurate IAQ assessments. It measures PM2.5 and PM10 from 0–999 μg/m^3 with ±10% accuracy, formaldehyde from 0–2 mg/m^3, and monitors temperature (0–50 °C), humidity (0-90% RH), and AQI. Readings were collected during peak traffic hours from January to February 2020.

The study used a rigorous methodology to assess IAQ and public awareness across commercial, healthcare, educational, hotel, and transport settings. IAQ was measured for 30 minutes, focusing on PM10, PM2.5, temperature, and humidity. Traffic-related pollutants were assessed in 10–15 vehicles over 10–15 minutes. A Google Forms questionnaire collected data on IAQ awareness, perceptions, and health effects, integrating quantitative measurements with insights from 100 participants. These questions are illustrated in **Figure 1**.

RESULTS AND DISCUSSION

Indoor lighting standards vary by activity and location. General spaces require 100–300 lux, while offices and classrooms need 300–500 lux for optimal visibility. More specialized tasks, such as laboratory work, may demand 750–1000 lux (IES, 2021). Adequate lighting enhances productivity, reduces eye strain, and supports overall well-being (Kim *et al.*, 2024).

The findings show variability in indoor illumination across Pune. Commercial areas like Shivaji Nagar (619 lux) and Magarpatta (556 lux) had high levels. Residential areas averaged below 150 lux. Schools and colleges showed moderate lighting. Hospitals and hotels varied, with Koregaon Park at 174 lux and Viman Nagar at 216 lux.

Table 1. Humidity Levels (%) at Various Indoor Study Sites in Pune

Area	Commercial Area	Residential Area	Shops	Colleges/ Schools	Hotels	Hospitals
Shivaji Nagar	57.2	51.5	54.1	56.4	56.7	54.2
Shaniwar Peth	51.4	51.4	52.4	56.4	56.5	54.9
Khadakwasala	61	62.1	63.2	54.3	65.4	54.3
Katraj	57.2	48.6	48.6	57.2	48.1	-
Koregaon Park	55.2	55.1	51.2	56.6	59.5	55.6
Magarpatta	52.3	41.5	50.3	50.4	43.1	50.1
Hinjewadi	58.2	66.5	50.5	51.2	50.2	50.2
Pashan	60.2	63.9	60.2	61.3	58.4	60.3
Vimannagar	48.2	46.8	42.5	45.2	44.1	42.7
Hadapsar	48.2	48.2	48.2	-	47.6	49.2

Indoor humidity impacts air quality, comfort, and building integrity. ASHRAE recommends maintaining relative humidity between 30% and 60% to reduce microbial growth and respiratory issues (ASHRAE, 2021). High humidity promotes mold growth, while low humidity causes respiratory discomfort (Du *et al*., 2021).

Humidity variations across indoor environments are influenced by factors such as ventilation, occupancy, and external climate, underscoring the necessity for continuous monitoring (Zuo *et al*., 2021). In Pune, indoor humidity varied. Hospitals, schools, and commercial spaces maintained moderate levels (50–60%) per ASHRAE. Residential areas showed more variation, with Hinjewadi (66.5%) and Pashan (63.9%) higher due to limited ventilation **(Table 1)**. Retail spaces and hotels showed humidity fluctuations, with some below 45%, risking discomfort. Koregaon Park and Khadakwasala exceeded 60%, possibly encouraging microbial growth. These trends stress the need for location-specific humidity control.

Commercial areas, hospitals, and schools-maintained temperatures between 28–30°C, indicating well-regulated environments, while residential neighborhoods showed more variation, particularly Magarpatta (31.6°C) and Hadapsar (31.2°C), exhibited higher temperatures, likely attributable to urban heat effects (Cuce *et al.*, 2025). Shops and hotels experienced the highest temperatures, peaking at 32.7°C in Magarpatta, which suggests significant heat retention (Hadavi & Pasdarshahri, 2021). Koregaon Park recorded the lowest temperature at 26.8°C, likely due to enhanced greenery and ventilation (Qiao *et al*., 2023). Commercial areas, hospitals, and schools had temperatures around 28-30°C. Residential zones like Magarpatta (31.6°C) and Hadapsar (31.2°C) were hotter due to urban heat. Shops and hotels in Magarpatta peaked at 32.7°C, while Koregaon Park was coolest (26.8°C), likely due to greenery and ventilation.

Table 2. PM10 Levels (μg/m³) at Various Indoor Study Sites in Pune

Area	Commercial Area	Residential Area	Shops	Colleges/ Schools	Hotels	Hospitals
Shivaji Nagar	76.2	278.2	164.4	131.6	226.2	121.2
Shaniwar Peth	86.4	86.2	158.2	210	247.4	128.2
Khadakwasala	136.8	116.2	102.9	134.1	163.7	121.1
Katraj	118.2	119.6	96.5	124.2	236	
Koregaon Park	146	126.1	134.8	142.2	148.2	156.5
Magarpatta	126.9	146.8	186.1	130.3	136	126.4
Hinjewadi	179.5	199.1	186.1	126.4	148.6	134.2
Pashan	124.2	146.6	128.8	126	130	112.1
Vimannagar	110.9	146.8	125.5	134.3	158	138
Hadapsar	71	109.6	128.2	-	110.1	138.6

Residential areas recorded some of the highest PM10 levels **(Table 2)**, notably in Shivaji Nagar (278.2 μg/m^3) and Hinjewadi (199.1 μg/m^3), likely attributable to inadequate air exchange and infiltration from traffic emissions (Mohammadi & Calautit, 2022). Hotels and commercial establishments also demonstrated elevated PM10 levels, peaking in Shaniwar Peth (247.4 μg/m^3) and Katraj (236 μg/m^3), potentially due to combustion sources, cooking activities, and high volumes of human activity (Ditto *et al*., 2023). Retail areas in Magarpatta and Hinjewadi (186.1 μg/m^3) showed high pollution from indoor sources and poor air filtration. In contrast, hospitals showed comparatively lower PM10 levels, likely due to controlled indoor environments and the implementation of air purification measures (Achilleos *et al*., 2023). These findings emphasize the need for better ventilation and pollution control.

Table 3. PM2.5 Levels (μg/m³) at Various Indoor Study Sites in Pune

Area	Commercial Area	Residential Area	Shops	Colleges/ Schools	Hotels	Hospitals
Shivaji Nagar	31.5	160.7	129.5	100.8	181.2	94
Shaniwar Peth	64.5	64.4	126	225.2	225.3	101.6
Khadakwasala	101.3	101	89.5	89.1	135.8	92.4
Katraj	99.2	117	89.3	100.4	225.4	-
Koregaon Park	120.1	117.8	120.6	120.1	126.4	132.8
Magarpatta	110.5	125.6	134.2	128.1	148	112.6
Hinjewadi	128.5	227.5	175.4	117.1	133.3	129.9
Pashan	116.1	107	113.5	118.2	128.7	106.2
Vimannagar	91.5	129	110.9	113.4	290	122.9
Hadapsar	67	98.4	104	-	96.2	126.2

Hotels and educational institutions reported the highest PM2.5 concentrations **(Table 3)**, particularly in Vimannagar (290 μg/m^3) and Shaniwar Peth (225.3 μg/m^3). These elevated levels are associated with cooking emissions, high occupancy rates, and inadequate ventilation (Rosário *et al*., 2021). Residential areas demonstrated a range of PM2.5 levels, with Hinjewadi recording the highest at 227.5 μg/m^3 and Shaniwar Peth the lowest at 64.4 μg/m^3, influenced by household activities and proximity to traffic (Liu *et al*., 2022). Commercial zones exhibited moderate PM2.5 levels, with Koregaon Park (120.1 μg/m^3) and Magarpatta (110.5 μg/m^3) experiencing elevated concentrations due to industrial and vehicular emissions (Hou *et al*., 2024).

Shops had higher PM2.5 levels than homes and hospitals, with Hinjewadi peaking at 175.4 μg/m^3 due to combustion and poor ventilation. Hospitals showed lower levels (92.4–132.8 μg/m^3) likely from better filtration, highlighting the need for improved IAQ management.

Table 4. Formaldehyde Levels (mg/m³) at Various Indoor Study Sites in Pune

Area	Commercial Area	Residential Area	Shops	Colleges/ Schools	Hotels	Hospitals
Shivaji Nagar	0.2	0.09	0.13	0.09	0.16	0.03
Shaniwar Peth	0.07	0.07	0.1	0.09	0.09	0.07
Khadakwasala	0.07	0.07	0.16	0.07	0.07	0.1
Katraj	0.06	0.09	0.04	0.07	0.2	-
Koregaon Park	0.06	0.02	0.08	0.05	0.09	0.11
Magarpatta	0.12	0.09	0.1	0.07	0.14	0.09
Hinjewadi	0.12	0.17	0.07	0.08	0.07	0.09
Pashan	0.06	0.21	0.09	0.08	0.09	0.1

Vimannagar	0.09	0.07	0.05	0.09	0.14	0.09
Hadapsar	0.07	0.07	0.07	-	0.09	0.08

Formaldehyde is a common indoor pollutant from building materials, furniture, and combustion sources. Research shows that levels are often higher in areas with extensive use of pressed wood products, adhesives, and certain textiles (Zhang *et al*., 2022). Liu *et al*. (2023) conducted a meta-analysis linking formaldehyde exposure in buildings to increased asthma risk in adults and children (García & Jaramillo, 2023; Grin *et al*., 2023; Ingle *et al*., 2023; Pavithra *et al*., 2023; Shaheen *et al*., 2023).

In Pune, formaldehyde concentrations vary across indoor environments **(Table 4)**. Hotels and commercial areas have the highest levels, with Shivaji Nagar and Katraj at 0.2 mg/m^3. Residential areas range from 0.21 mg/m^3 in Pashan to 0.02 mg/m^3 in Koregaon Park. Shops peak at 0.16 mg/m^3 in Khadakwasala, while educational institutions and hospitals show lower levels.

Table 5. Air Quality Index at Various Indoor Study Sites in Pune

Area	Commercial Area	Residential Area	Shops	Colleges/ Schools	Hotels	Hospitals
Shivaji Nagar	46	279	164	130	223	124
Shaniwar Peth	72	81	112	276	118	124
Khadakwasala	116	106.6	118	119	124	107
Katraj	89	118	109	106	275	-
Koregaon Park	155	141	140	128	160	169
Magarpatta	135	155	151	129	148	121
Hinjewadi	158	173	156	120	130	123
Pashan	104	139	111	104	120	100
Vimannagar	109	124	117	125	336	121
Hadapsar	82	128	139	-	108	148

The Air Quality Index (AQI) **(Table 5)** data notably in residential areas like Shivaji Nagar (AQI 279) and Vimannagar (AQI 336) exhibit alarmingly high pollution levels, which may be attributed to factors such as vehicular emissions, construction activities, and inadequate ventilation systems (World Health Organization, 2021). In contrast, commercial areas generally present lower AQI values, exemplified by Shivaji Nagar (AQI 46), suggesting relatively better air quality in these zones. However, hotels and hospitals, particularly in Vimannagar (AQI 336), report concerningly high AQI levels, raising concerns about air quality in environments frequented by vulnerable populations (Fu *et al*., 2022). Koregaon Park and Hinjewadi consistently show elevated AQI values across multiple categories. These findings underscore the urgent need for targeted measures to address indoor air pollution (Kumar *et al*., 2023). The data highlights the need for a comprehensive approach to mitigate indoor air pollution.

Spatial trends and variations

Hotels consistently had the highest PM10 and PM2.5 levels, due to cooking emissions, smoking, and poor ventilation. Residential areas had moderate PM levels, with some locations experiencing spikes from external factors like construction or vehicular emissions. Commercial spaces and shops recorded the lowest PM levels, indicating better ventilation and fewer pollutant sources.

Critical observations

Hotels show elevated PM concentrations due to poor air purification, high occupancy, and external pollutants, requiring immediate management. Residential areas have moderate PM levels, with occasional spikes from traffic or construction, highlighting the need for better ventilation. Hospitals and schools generally have better air quality, but anomalies in high-pollution areas stress the need for stricter IAQ protocols. Shops and commercial spaces report cleaner air, likely due to lower occupancy and controlled environments.

Area insights

Locations like Magarpatta show alarmingly high PM levels, especially in hotels, raising public health concerns. Shivaji Nagar and Shaniwar Peth exhibit similar trends, with elevated pollutant concentrations in hotels but better air quality in residential and commercial spaces. In areas like Pashan and Hinjewadi, residential zones occasionally report increased PM levels, likely due to local construction, traffic, or inadequate ventilation.

General trends and implications

Indoor environments with high occupancy, like hotels and restaurants, often have poor IAQ due to activities like cooking and smoking, with inadequate ventilation. In contrast, spaces with fewer pollutant sources and better air circulation, such as shops and commercial areas, maintain healthier air quality. Elevated PM levels in urbanized regions (e.g., Magarpatta, Koregaon Park) highlight the impact of external pollution.

Table 6. Parameter Levels for Indoor Vehicle Environment in Pune

Category	Vehicle Type	Temperature (°C)	PM10 (µg/m^3)	PM2.5 (µg/m^3)	HCHO (mg/m^3)	AQI
Private Vehicles	Hatchback 1	30.8	90	117.5	0.11	152
	Hatchback 2	31.9	41	27.3	0.16	34

	Compact Hatchback	31.3	78.5	54.2	0.17	74
	Sedan 1	31.7	129.1	87.7	0.27	117
	Sedan 2	31.5	76.5	90.3	0.17	106
	Sedan 3	29.1	136.1	92.1	0.13	127
	SUV 1	28.5	92	65.3	0.12	100
	SUV 2	29.1	114.3	78.3	0.11	109
	Large SUV	30	151.4	111.9	0.14	128
	SUV 3	32.2	96	75.2	0.16	99
Public Transport	Diesel Bus	31	138.3	111.2	0.1	134
	CNG Bus	31.2	146	124.6	0.14	136
	Electric Bus	25	126.3	108.5	0.15	129

Levels of PM10 and PM2.5 within vehicles **(Table 6)** are influenced by traffic conditions, ventilation settings, and fuel type, resulting in notable disparities in air quality (Hou *et al*., 2024). Concentrations of formaldehyde, associated with interior materials and ventilation efficiency, frequently exceed recommended limits, posing potential health risks (Wang *et al*., 2023). The transportation sector is a major source of greenhouse gas emissions and plays a significant role in deteriorating urban air quality with higher AQI (Tsai & Lin, 2021).

IAQ in vehicle cabins across Pune was assessed based on temperature, PM10, PM2.5, AQI, and formaldehyde levels (Makhoahle, & Gaseitsiwe, 2022). Public transport had poorer IAQ than private vehicles due to higher passenger turnover and pollutant infiltration. The highest PM10 levels were found in SUVs (151.4 μg/m^3) and CNG buses (146 μg/m^3), while PM2.5 levels peaked in CNG buses (124.6 μg/m^3), indicating poor ventilation (Cortés *et al*., 2024; Gioia *et al*., 2024; Li *et al*., 2024; Omokunle, 2024; Schanzempch & Rimoldi, 2024). The worst AQI (152) was recorded in a hatchback, followed by CNG buses (136). Formaldehyde peaked in a sedan (0.27 mg/m^3), likely from plastic and adhesive emissions (AlHumaidi *et al*., 2022; Deana *et al*., 2022; Mahmood *et al*., 2022; Spirito *et al*., 2022).

IAQ in vehicle cabins across Pune was assessed based on temperature, PM10, PM2.5, AQI, and formaldehyde levels. Public transport had poorer IAQ than private vehicles due to higher passenger turnover and pollutant infiltration. The highest PM10 levels were found in SUVs (151.4 μg/m^3) and CNG buses (146 μg/m^3), with CNG buses also showing the highest PM2.5 levels (124.6 μg/m^3). The worst AQI (152) was in a hatchback, followed by CNG buses (136). Formaldehyde peaked in a sedan (0.27 mg/m^3), likely from plastic and adhesive emissions. Larger vehicles, including SUVs and buses, showed elevated PM levels. Improving air purification, optimizing airflow, and raising public awareness can enhance IAQ (Carlsten *et al*., 2020; Fu *et al*., 2022).

Survey analysis

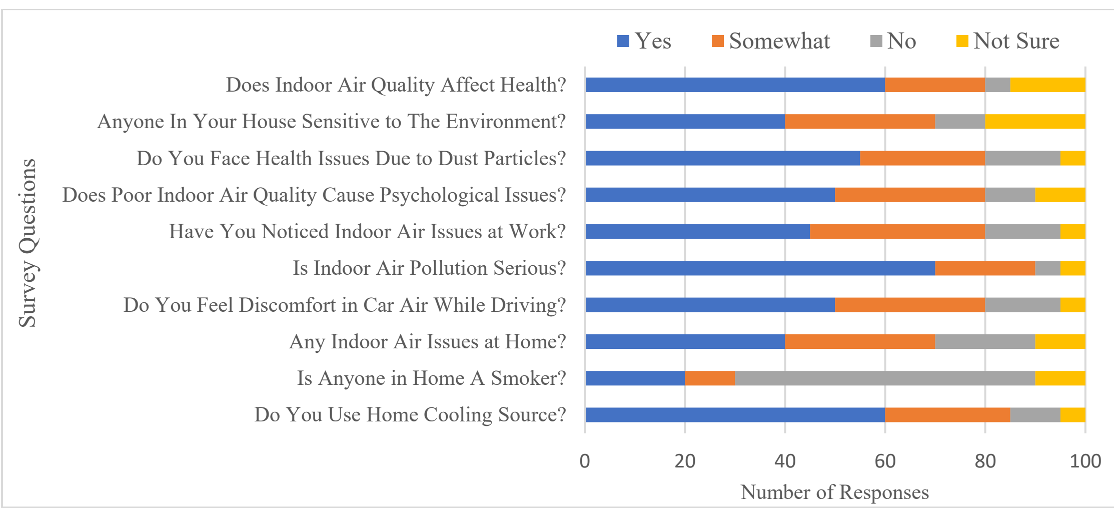

Figure 1. Survey Analysis on Indoor Air Quality

Indoor air pollution affects health, with 33% of respondents reporting respiratory issues and 40% experiencing allergies, mainly due to dust. Poor air quality from dust, mold, and allergens causes breathing difficulties and allergic reactions. Additionally, 40% reported skin irritation from dust, highlighting the impact of PM2.5, PM10, and chemicals on both respiratory and skin health (Burghate & Mundada, 2023: Graefen *et al*., 2023). There is need for improved air quality management through enhanced ventilation, air purification, and regular cleaning practices (Pignon *et al*., 2022; Jaganathan *et al*., 2025).

The survey shows many respondents face health issues due to dust and indoor air quality, with some unaware of the psychological effects. While many reported no air quality problems at home or work, most use cooling systems that may impact indoor conditions. Smoking at home is rare, as most do not smoke (Bandi *et al*., 2024; Erlina *et al*., 2024; Uneno *et al*., 2024). These findings highlight the importance of improving ventilation, air purification, and increasing awareness of indoor pollution sources (Cheek *et al*., 2021; Fu *et al*., 2022).

CONCLUSION

This study reveals significant variations in indoor air quality (IAQ) across Pune, with hotels identified as high-risk areas due to elevated PM10 and PM2.5 concentrations. Residential areas showed moderate IAQ, but traffic emissions caused pollution spikes. Commercial spaces had better air quality, likely due to controlled environments and efficient ventilation. Public transport vehicles, especially diesel and CNG buses, displayed poor IAQ with high particulate matter concentrations and AQI values exceeding safe limits. This highlights the need for improved air filtration and ventilation in buses to protect passengers. Private vehicles, including hatchbacks and sedans, also recorded high pollutant levels due to inadequate ventilation and emissions from interiors.

Survey results confirm the health impacts of poor IAQ, with many respondents reporting respiratory issues and discomfort. Formaldehyde in vehicle cabins highlights the need for better air purification. Limited awareness of indoor pollution calls for public education and policy action. Promoting healthier environments requires air filtration, sustainable building design, and regular assessments. Collaboration between manufacturers and policymakers is essential to improve vehicle ventilation and filtration. Targeted strategies are crucial to reduce indoor pollution and improve well-being.

ACKNOWLEDGMENTS: Authors sincerely thank Principal of Fergusson College, Pune, for providing the facilities for this research. We also appreciate the management of the Deccan Education Society, Pune, for their ongoing support and encouragement throughout the study.

CONFLICT OF INTEREST: None

FINANCIAL SUPPORT: None

ETHICS STATEMENT: None

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